Ecosystem Services of the Deep Ocean

Jennifer T. Le
and Kirk N. Sato

The concept of ecosystem services (ES) includes the ecological functions and the economic value of ecosystems which contribute to human well-being. This approach is already applied to coastal water management, but it is rarely applied to the deep sea although it represents 97% of the ocean's volume. Deep-sea ES include provisioning services such as fish catch or industrial agents, regulation services such as carbon storage, and cultural services such as inspiration for the arts. However, the deep sea is facing increasing pressures in the form of direct and indirect human activities. This synergy of impacts is widely unknown and the lack of regulation regarding certain parts of the ocean requires great caution.

INTRODUCTION TO ECOSYSTEM SERVICES IN THE DEEP SEA

Ecosystem services (ES) are generally defined as contributions to human well-being from ecosystems (MEA, 2005; TEEB, 2010; Haines-Young and Potschin, 2013). The concept integrates ecological functions and economic values to explain how ecosystem health affects the socio-economic system. ES can be assigned monetary values for use in decision-making, and incorporated into management tools such as marine spatial planning and ecosystem-based management (Jobstvogt *et al.*, 2014). An ES approach has previously been used in terrestrial and shallow water systems (*e.g.*, Seidl *et al.*, 2016; Gunderson *et al.*, 2016), but its application to the deep sea has been extremely limited.

Figure 1 illustrates deep-sea ecosystem services (DSES) that fall into the categories often used to describe ES: provisioning (outputs gained from ecosystems), regulating (regulation of environmental processes), and cultural (non-material benefits). Deep-sea provisioning services include fisheries landings, pharmaceuticals, industrial agents, and biomaterials (Leary, 2004; Mahon *et al.*, 2015). Examples of regulating services are climate regulation, biological controls, and waste absorption (Armstrong *et al.*, 2012; Thurber *et al.*, 2014). There are also cultural services associated with the deep sea, such as educational benefits, aesthetics and inspiration for the arts, the value of knowing a resource exists, and the value of protecting a resource for current and future generations. Many deep-sea functions (*e.g.*, primary biodiversity, element cycling) directly and indirectly contribute to these services, and must also be kept in mind to continue benefitting from DSES. For example, a deep-sea function that supports fisheries is nutrient regeneration (Thurber *et al.*, 2014), which occurs mainly in regions of strong upwelling (*e.g.*, eastern boundary currents, Antarctica), but also in areas where local upwelling can occur (*e.g.*, mesoscale eddies, seamounts). Upwelled nutrients from the deep-sea fuel photosynthesis, which in turn supports major fisheries such as sardines and anchovies.

Increasing human activity in the deep sea has created an urgent need for evaluating impacts on ecosystem health. Anthropogenic carbon dioxide CO_2 emissions have resulted in warming, deoxygenation, and acidification that will change how direct human activity (*e.g.*, fishing, oil and gas drilling, mine tailings placement) impacts deep-sea habitats. In the midst of these cumulative impacts on the deep sea, it is important to consider DSES, how they might be affected, and how to best manage them.

DSES OF CLIMATE REGULATION

The ocean has absorbed approximately one-third of emitted CO_2 (IPCC, 2014) through physical, chemical and biological processes. The deep ocean system serves as a major heat sink and slows down anthropogenic global warming (IPCC, 2014); thus, CO_2 absorbance by the deep sea is a very important climate-regulating service (Thurber *et al.*, 2014). Climate regulation, including carbon sequestration, will continue to be a critically important service provided by the deep sea as CO_2 emissions continue to increase. Warming, deoxygenation, acidification, nutrient changes, and calcium carbonate undersaturation are major ocean climate drivers that will interact with human activities in the deep sea, and future studies need to assess the complex cumulative impacts on deep-sea biodiversity, functioning, and DSES.

Carbon sequestration by the deep ocean is an important climate change mitigation pathway that relies on an efficient "biological pump" (*i.e.*, the physical process of sinking biologically-produced carbon from the upper ocean into the deep sea). The burial of upper ocean-produced carbon in deep sediments contributes to carbon sequestration and climate regulation because it removes the carbon from the atmosphere for thousands to millions of years (Xiao *et al.*, 2010). In addition, this sinking carbon is an important food source for many larger organisms that support deep-sea fishery species. How global climate change affects the biological pump and consequent export and sequestration of carbon to the deep sea remains an important topic of ongoing research (for review, see Turner, 2015), but long-term observations show that trends will vary depending on the region of interest (Levin and Le Bris, 2015).

Greenhouse gases such as methane (CH_4) and CO_2 enter the ocean naturally from deep-seafloor geologic structures such as hydrothermal vents and methane seeps. However, biological fixation of CH_4 and CO_2 by micro- and macroorganisms in these deep-sea ecosystems prevents these gases from entering the water column. This biological filtering of CH_4 and CO_2 at the seafloor is another regulating service and is an important process that indirectly supports commercially fished species (Thurber *et al.*, 2014).

DIRECT HUMAN ACTIVITIES IN THE DEEP

In addition to impacts related to climate, direct human activity in the deep sea is also increasing (Ramirez-Llodra *et al.*, 2011). The deep sea contains a wealth of natural resources and extracting them can be harmful to its many, heterogenous habitats. For example, as global demand and human consumption of fish increase (FAO, 2014), fisheries are moving deeper into the water column and seabed (Watson and Morato, 2013). Trawling disturbs and removes physical structures and sediment on the seabed which can lead to loss of both targeted species and those associated with the seabed (Buhl-Mortensen *et al.*, 2015). In addition, deep-sea fisheries species may take longer to recover because many have longer life spans relative to shallow water species (Norse *et al.*, 2012).

Other extractive activities include oil and gas, and potentially minerals. Oil and gas exploration and drilling are also moving into deeper waters, increasing the risk of oil spills (*e.g.*, Deepwater Horizon; Merrie *et al.*, 2014). Deep-seabed mining regulation under

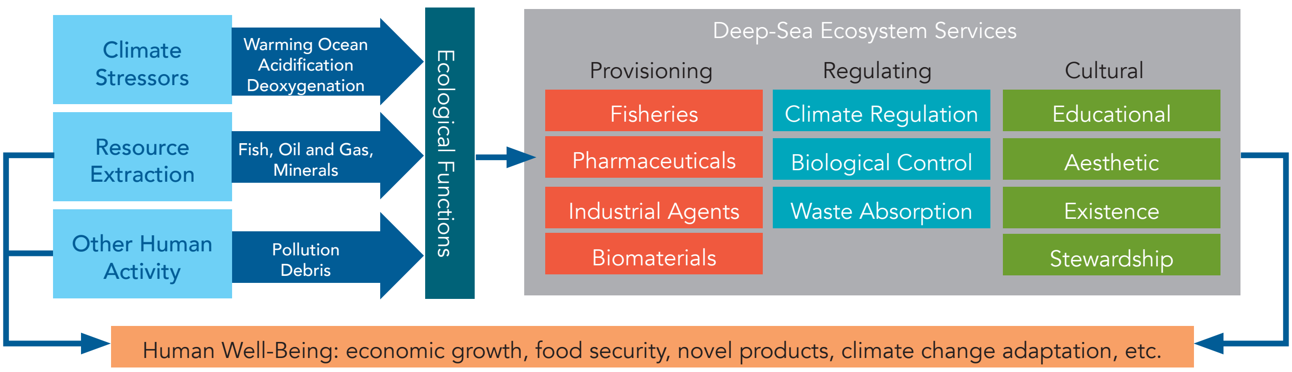

Fig.1 — The relationship among anthropogenic climate change stressors, deep-sea ecosystem services, and human well-being. © J. T. Le and K. N. Sato.

commercial exploitation is currently in development (ISA, 2015). Different mineral deposits of interest are found on hydrothermal vents, seamounts, and abyssal plains, which all host different biological communities that can contribute differentially to DSES. Disturbance of these ecosystems via direct human impacts such as mining, trawling, and other extractive activities (*e.g.*, oil and gas drilling) will likely disrupt this regulatory function with high risk for acute and long-term loss of services.

POTENTIAL IMPACTS OF SYNERGISMS (CLIMATE AND HUMAN ACTIVITIES)

The cumulative impact of multiple climate stressors and extractive activities can lead to additive, antagonistic, or synergistic effects on DSES (Crain *et al.*, 2008). Deep-sea ecosystem functions are not well constrained, nor are the interactions and dynamics between them. This makes it difficult to predict how the provision of DSES will change due to both direct and indirect human impact. This may invoke the precautionary principle (Rio Declaration, 1992), and highlight the need for novel approaches in better understanding the deep sea and the benefits it provides.

The consequences of warming in deep ocean waters will not only influence the regulatory service the deep sea provides as a heat sink, but it will profoundly affect ecosystems and their biodiversity, given the stability of this cold environment. For example, warming in South America has induced poleward range shifts in predatory crab to the Antarctic where communities have evolved without the presence of crushing predators for millions of years (Smith *et al.*, 2012). The combination of warming, acidification, and deoxygenation, described as a "triple whammy" of stressors, is predicted to reduce habitat suitability for habitat-forming calcifiers such as cold-water corals (Gruber, 2011; Lunden *et al.*, 2014). Biodiversity also plays a key functional role in the provision of most other ES (Palumbi *et al.*, 2009; Science for Environment Policy, 2015), although the exact relationship remains unclear (Balvanera *et al.*, 2014). As these impacts continue to reveal themselves, deep-sea biological communities grow increasingly vulnerable.

JURISDICTIONAL CHALLENGES OF DSES IMPLEMENTATION

There exist challenges to the operationalization of an ES approach in the deep sea. These include how functions translate into services, recovery potential and times, and the economic valuation of ES, which are related to lack of knowledge and data (Le *et al.*, in press). Other challenges, such as those regarding jurisdiction and enforcement, are borne out of gaps in a regulatory framework still in development.

The deep sea is the largest ecosystem on Earth, making up more than 90% of the liveable volume on the planet (Levin and Le Bris, 2015). However, most of it lies outside of countries' exclusive economic zones (EEZs) and must, therefore, be regulated and managed internationally. A common management tool is marine spatial planning, which could potentially utilize DSES in designating marine protected areas (MPAs). For example, an ES-value threshold could be established with baseline estimates of ES provision, and any areas that provide ES with value higher than that threshold could be given spatial protections. The international nature of many deep-sea resources makes this difficult because of overlaps and gaps in jurisdiction, and differences in management tools.

In general, MPAs exhibit higher resilience to and recovery potential after disturbance events (Huvenne *et al.*, 2016). In Areas Beyond National Jurisdiction (ABNJ), the Food and Agriculture Organization of the United Nations (FAO) has designated several deep-water species and habitats as Vulnerable Marine Ecosystems (VMEs) (*e.g.*, cold-water corals, hydrothermal vents on Reyjkanes Ridge, C-H seamounts in the Pacific). Generally, once identified, VMEs are protected from all human activities, but different management regulations may allow some fishing activity in certain protected areas (*e.g.*, MPAs).

The International Seabed Authority (ISA) has jurisdiction in ABNJ, although only on the seafloor. In addition to recognizing VMEs, the ISA can designate spatial protections called areas of particular environmental interest (APEIs) (ISA, 2011). Large sections of the Clarion-Clipperton Fracture Zone, which is a polymetallic nodule province with multiple mining exploration claims within it, have been designated as APEIs (Wedding *et al.*, 2013). Other protections in international waters include the recent "biodiversity beyond national jurisdiction" (BBNJ) instrument that the United Nations is developing (Blasiak and Yagi, 2016).

Marine Reserves (MRVs), another type of MPA where no resource extraction is allowed, are effective at increasing the abundance, diversity, and productivity of marine organisms (Lubchenco *et al.*, 2003). Furthermore, larger networks of MRVs are effective at maintaining connectivity among populations, thereby providing more protection for marine communities than a single MRV against climate change. As marine species shift their ranges from changes in temperature, oxygen, or carbonate chemistry, it is important that networks of MRVs consider novel conservation planning approaches that incorporate climate change adaptations in organisms and humans (Schmitz *et al.*, 2015; Jones *et al.*, 2016).

MPAs are important management tools because they can protect areas that provide ES and, consequently, significant value to society. Incorporating ES into spatial protections would associate a value with the MPA (i.e., the value of a MPA would be equal to the value of the ES it provides, both directly and indirectly). Estimated values of an MPA may help further inform decisions regarding enforcement (*e.g.*, how much to provide, who is responsible). Although economic valuation is currently difficult, it will become more manageable and accurate as more knowledge and data regarding DSES accrue.

THE DSES "CHARISMA" GAP

Another challenge to implementing a DSES approach to management in the face of multiple climate stressors and human activities is the lack of understanding and "charisma" about the deep sea by the general public. Humans are physically and emotionally disconnected from the deep-sea environment, even more so than other ES that are out of sight (*e.g.*, Blue Carbon). The most effective way to fill this "charisma" gap is to improve scientific understanding, stewardship, and public education. It is more important than ever to raise awareness and promote transparency, accountability, research, and conservation of DSES. For example, the Deep Ocean Stewardship Initiative (DOSI) is a group of international scientists and professionals in technology, policy, law and economics that advises on ecosystem-based management of resource use in the deep sea and potential strategies that maintain the integrity of deep-sea ecosystems within and beyond national jurisdiction (http://dosi-project.org/). Live web broadcasting from the deep sea by the NOAA Office of Ocean Exploration and Research offers anyone with an internet connection the experience to witness what biological and earth processes occur in the deep ocean. Amid other deep-sea researchers and explorers, these organizations emphasize the importance of interdisciplinary approaches to better understand how the deep ocean functions and how the services it provides will change under future climate change scenarios.

CONCLUSION

The deep sea is the largest ecosystem on Earth and hosts a diversity of habitats that provide value to society as a result of their functioning. These ecosystem services can be extractive (*e.g.*, fishing) or non-extractive (*e.g.*, climate regulation), and it is essential to consider both in environmental management especially in the face of multiple stressors related to climate and human activity. As CO_2 emissions continue to increase, deep-sea climate regulation may become increasingly important to recognize in order to continue benefitting from this service, which also influences other services related to biogeochemical cycles and biological communities (Fig. 1). Although there are still challenges to be addressed in the deep sea (*e.g.*, scientific uncertainty, jurisdictional gaps, lack of public engagement), development of protective measures against environmental degradation and emergencies now may help ensure the environmentally and economically sustainable use of the deep sea and its many ecosystem services.

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